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# Design of innovative power conditioning system for the grid integration of thermoelectric generators☆

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ABSTRACT

Recently, thermoelectric generators (TEGs) have emerged as a potential alternative for clean energy generation, due mainly to the technology innovation and the marked cost reduction of modules, as well as their distinctive advantages. In a TEG system, the electronic power conditioning system (PCS) plays a vital role in ensuring the effective power grid integration, since it is subject to requirements related not only to the variable thermal source itself but also to its effects on the grid operation. This paper proposes an enhanced structure of PCS for the grid integration of TEG arrays to maximize the energy capture from a variable heat source. The innovative topology employed consists of a Z-source inverter that allows the flexible, efficient and reliable generation of high quality electric power from the TEG array. A full detailed model is described and its control scheme is designed. The dynamic performance of the proposed systems is fully validated by computer simulation and experimental studies.



## 1. Introduction

In recent years, there has been an extensive growth and rapid development in the exploitation of renewable energy sources (RESs) that do not cause environmental pollution, such as wind, solar, thermal, etc., mainly due to the technological development, cost reduction, and government policy stimulus [1]. Among these RESs, thermal power generation with solid-state devices, aka thermoelectric generators (TEGs) or thermopiles, has emerged as a potential alternative for clean energy generation [2], mostly caused by the noticeable cost reduction of modules as a result of an increase in the world production, as well as their distinctive benefits. They include the capability to generate electricity continually while they are provided with heat, simplicity of allocation, low maintenance, long life span and high reliability [3].

A TEG module allows generating DC electricity directly and with no moving parts from a temperature difference held across the junction of two different semiconductor materials. These devices have been employed worldwide for the provision of electricity to small DC loads in isolated regions in the oil industry for at least 40 years. However, TEGs are presently

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arising as a feasible option inside the portfolio of new sustainable energy sources connected to the utility grid. This solution is known as distributed or dispersed generation (DG) and consists of using small-size generating units integrated into the distribution network as near as possible of the end-user loads. In these grid-interactive applications of TEG systems, the electronic power conditioning system (PCS) plays an important role in ensuring the effective power grid integration, since it is subject to requirements related not only to the variable source itself but also to its effects on the electric systems operation.

This paper describes the design, simulation and implementation of a high performance PCS of a three-phase grid-connected TEG system and its control scheme to maximize the energy capture from a variable heat source. The proposed PCS utilizes a simple and innovative structure that differs from the conventional ones, such as the presented in [4], in the use of a single-stage power conversion topology that offers significant advantages. The converter corresponds to a three-phase Z-source inverter that allows the flexible, efficient and reliable generation of high quality electric power from the TEG array. The dynamic performance of the proposed system is fully validated by computer simulation and experimental studies.

## 2. Model of the proposed TEG system

The basic structure of the proposed TEG system for applications in distributed generation systems consists of the TEG array and its power conditioning system for connecting to the electric grid, as summarized in Fig. 1.

### 2.1. TEG module/array

The schematic diagram of the thermoelectric generator module is shown in Fig. 2 [5]. A TEG consists of two dissimilar materials, n-type and p-type semiconductors, connected electrically in series and thermally in parallel. Heat is supplied at one end, i.e. the hot junction, at a temperature $T_{Hg}$, while the other end, that is the cold junction, is maintained at a lower temperature $T_{Lg}$ (usually using a very low–thermal resistance heat sink with forced convection). As a result of the temperature difference $\Delta T_g$ between both junctions and the consequent established heat flux, an electromotive force (emf) $V_{Thg}$ is generated according to the Seebeck coefficient $\alpha_g$ (V/°C) of the TEG semiconductor material, as:

$$\alpha_g = \frac{\Delta V_{Thg}}{\Delta T_g} \tag{1}$$

This coefficient is sometimes called the thermal emf coefficient or thermoelectric power and is directly related to the energy band gap of the material. The built-in electrostatic potential generates an output voltage $V_g$ as a consequence of a current $I_g$ flowing through an external load resistance. As can be noted, the power output depends upon the temperature difference, the physical properties of the semiconductor materials and the external load resistance. A dimensionless figure-of-merit $Z$ is usually employed as a measure of efficiency of materials in thermoelectric generation, defined as [3]:

$$Z = \frac{\alpha_g^2 \sigma_g}{(\lambda_e + \lambda_p)}, \tag{2}$$

where $\sigma_g$ is the electrical conductivity, and $\lambda_e$ and $\lambda_p$ are the electronic and lattice components of the thermal conductivity, respectively. The numerator of this expression is the so-called power factor.

For the heat conduction effect, the Joulean heat and the energy supply or removal to overcome the Peltier-Seebeck effects are combined for the whole generator arrangement. The rate of heat supply $Q_{Hg}$ and heat removal $Q_{Lg}$, the output generated voltage $V_g$, the net output power $P_g$ and the thermal efficiency $\eta$ are given by Equation (3) through (7), as follows [5]:

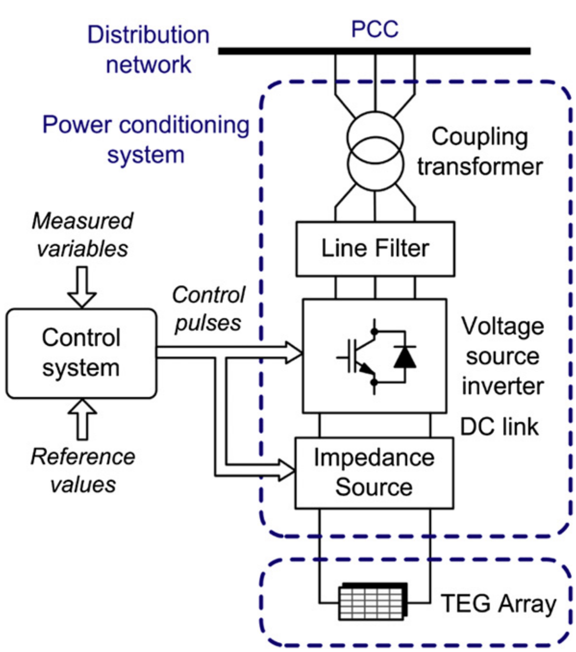


Fig. 1 – Basic structure of the TEG system.

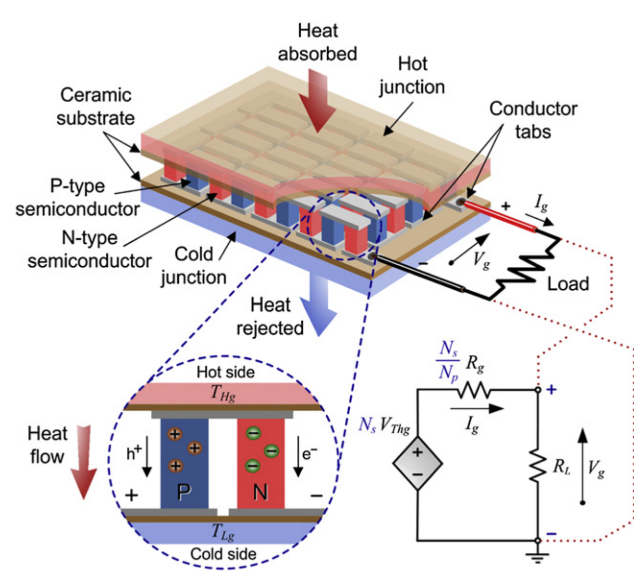


Fig. 2 – Schematic diagram of the TEG module.

The rate of heat supply,

$$Q_{Hg} = \alpha_g I_g T_{Hg} - 1/2 I_g^2 R_g + k_g (T_{Hg} - T_{Lg}) \tag{3}$$

The rate of heat removal,

$$Q_{Lg} = \alpha_g I_g T_{Lg} - 1/2 I_g^2 R_g + k_g (T_{Hg} - T_{Lg}) \tag{4}$$

The output voltage,

$$V_g = \alpha_g (T_{Hg} - T_{Lg}) - I_g R_g \tag{5}$$

The net output power,

$$P_g = \alpha_g I_g (T_{Hg} - T_{Lg}) - I_g^2 R_g, \tag{6}$$

and the thermal efficiency,

$$\eta = \frac{P_g}{Q_{Hg}} \tag{7}$$

As can be clearly derived from the above equations, a TEG single thermocouple can be modelled as an equivalent circuit composed of a thermally generated voltage source $V_{Thg}$ and a series intrinsic resistance $R_g$, as depicted in the Fig. 2 (lower right side). The generated emf $V_{Thg}$ depends on both the temperature gap ($\Delta T_g = T_{Hg} - T_{Lg}$) and the Seebeck coefficient $\alpha_g$ of the TEG semiconductor material. On the other hand, the rate of heat supply/removal is additionally a function of the total thermal conductivity $k_g$ (W/°K) of the thermoelectric generator. In fact, TEG thermocouples are grouped together in larger units known as TEG modules or arrays, which are electrically combined in series and stacked in parallel to provide the desired output voltage and current. The equivalent circuit for the TEG thermocouples arranged in $N_p$–parallel and $N_s$–series is directly extended from the single model, as pointed out in the same figure.

An experimental set-up was assembled in the laboratory in order to study two commercially available $Bi_2Te_3$-based alloy thermoelectric generators, i.e. the Hi–Z [6] and the Tellurex [7] TEG modules. Maintaining roughly constant the temperature of the source and the drain of heat, the power generated was measured as a function of the load resistance connected, operating in steady-state conditions all the time. Under this situation, Fig. 3(a) depicts the measured output power versus current curves, for an HZ–20 TEG module from Hi–Z (rated for 19W at $\Delta T_g$ = 230–30° C) tested in the laboratory for various average temperatures $T_{Avg} = (T_{Hg} + T_{Lg})/2$, but maintaining the same temperature gradient $\Delta T_g = T_{Hg} - T_{Lg}$ around 200 °C. In the same way, Fig. 3(b) shows the same measured output P–I characteristic curves, for a G1-1.4 TEG module from Tellurex (power rating of 7.2 W at $\Delta T_g$ = 150–50°C) with two average temperature series and a constant temperature gap of 100 °C between both TEG sides.

As can be derived from experimental results, significant issues concerning the behaviour of the TEG device can be stated, as follows:

- There exists a parabolic dependence of the output power from the output current.
- The power provided by the TEG array to the load varies with the average temperature $T_{Avg}$ for a specific temperature gradient following an inversely proportional relationship.

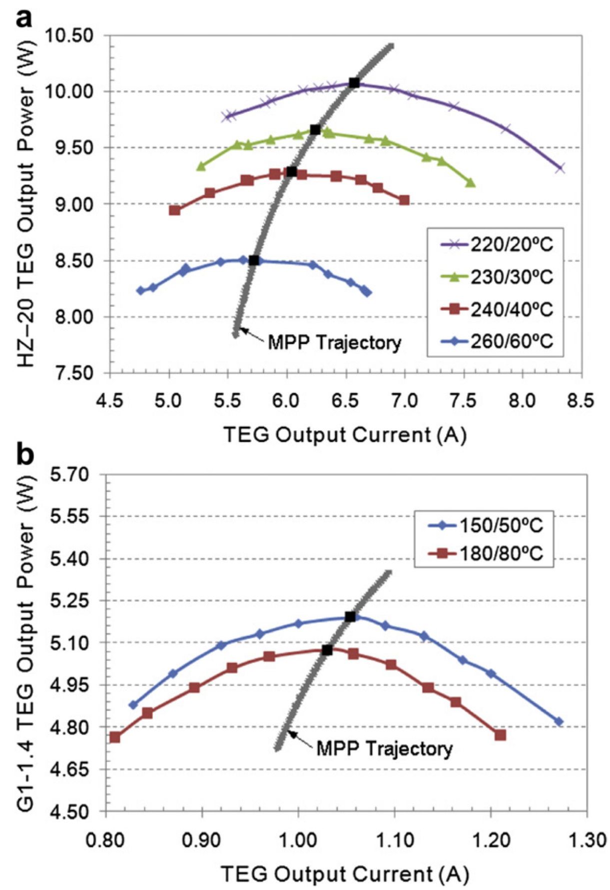


**Fig. 3 – Commercial TEG characteristic curves measured for various $T_{Hg}$ and $T_{Lg}$. (a) $P_g/I_g$ curve for an HZ–20 module (Hi–Z). (b) $P_g/I_g$ curve for a G1–1.4 module (Tellurex).**

- The maximum power point (MPP) is obtained when the load equals the internal resistance of the TEG.
- The internal resistance of the TEG array varies with the temperature of the evaluated temperature series following a proportional relationship, as derived from measurements of Fig. 4(a) for the HZ–20 TEG.
- The generated emf $V_{Thg}$ varies with the temperature of the evaluated temperature series following an inversely proportional relationship as in the case of power. This is a consequence of the inverse variation of the Seebeck coefficient $\alpha_g$ with the average temperature for a given temperature gap. Fig. 4(b) shows the output voltage generated by $V_{Thg}$ as a function of the current drawn from the HZ–20.

For providing maximum power to the load and thus optimizing the efficiency of the TEG system operating with a variable thermal source, as is usually the case, a continuous matching of the load resistance to the module internal resistance is required. This implies a constant knowledge of the TEG internal total resistance, in order to allow the TEG operation inside the optimal trajectory at all times, as described in Fig. 3 through 4 in solid gray line (MPP trajectory). As was derived from experimental results, the intrinsic series

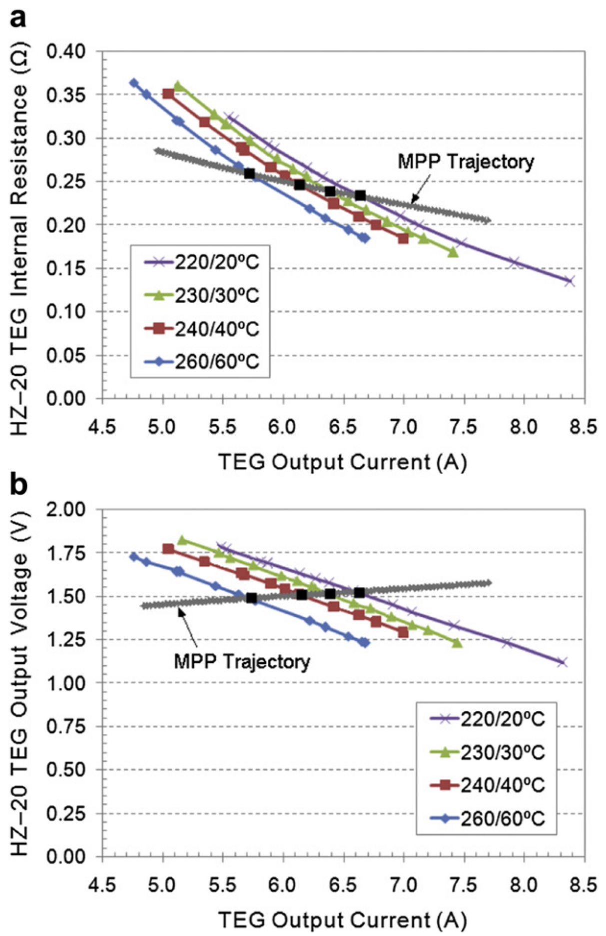


**Fig. 4 – HZ–20 TEG module (Hi–Z) curves measured for various $T_{Hg}$ and $T_{Lg}$. (a) $R_g/I_g$ curve. (b) $V_g/I_g$ curve.**

resistance of the TEG array varies with the average temperatures $T_{Avg}$, even when the temperature gap between junctions is maintained constant. Since the TEG device expands when is heated, and contracts when is cold down, the contact pressure is varied and therefore the thermal contact resistance is also changed. This is translated as a variation of the effective temperature gradient of the array and eventually as a variation in the emf induced and in the internal resistance.

### 2.2. Power conditioning system

The main purpose of a grid-connected thermoelectric generating system is to transfer the maximum power obtained from a heat source into the electric utility grid while meeting the specific electrical grid code requirements. This goal imposes the necessity of using an appropriate electronic interface that allows three major goals: one is to convert electric power from DC to AC, second is to control efficiently the operation of the TEG array near the maximum power point (MPP) at all times independently of the thermal operating conditions and lastly is to provide reactive power locally and with no extra passive devices [5].

The power conditioning system (PCS) is the electronic device that permits to achieve this objective by successfully controlling the active power flow exchanged with the electric system. With its appropriate topology and control system, the TEG is capable of simultaneously and independently performing both instantaneous active and reactive power flow control, as required by modern grid-connected applications. To this aim, a PCS hardware configuration of two cascade stages is the most common solution used [4], which offers an additional degree of freedom in the operation of the TEG system when compared with the classical single-stage configuration. Generally, it is achieved at the expense of decreasing the global efficiency of the overall system. Hence, a three-phase DC/AC voltage source inverter (VSI) using IGBTs (Insulated Gate Bipolar Transistors) are employed for connecting to the grid. This three-phase static device is shunt-connected to the distribution network in the so-called point of common coupling (PCC) by means of a coupling transformer and the corresponding line sinusoidal filter, as depicted in Fig. 5. The output voltage control of this VSI can be efficiently achieved through pulse width modulation (PWM) techniques.

As the VSI needs a fixed DC link in order to allow a decoupled control of both active and reactive power exchange with the electric grid, an extra conditioner utilized as interface in the DC side of the VSI is required. For this purpose, an intermediate DC/DC converter (or chopper) in a boost topology is generally employed [4]. However, it still retains some disadvantages when compared to single-stage topologies, among which excels the reduced power conversion efficiency, reduced reliability, and higher volume and weight.

To overcome these problems, this paper proposes the use of a novel inverter topology capable of coping with the output voltage variation of the primary energy source and still preserving a fixed higher voltage DC link, all in one single-stage. This structure utilized to realize both inversion and boost function in a single stage is an impedance-source (or impedance-fed) power inverter (aka Z-source inverter) [8], which is represented in Fig. 5. A unique impedance source (Z-source), consisting of a two-port network with a couple of inductors and capacitors connected in X shape, is used for coupling the TEG array to the standard three-phase VSI. In this way, with the proper design of the PWM scheme to the inverter, the voltage boosting (or bucking) function can be realized simultaneously and independently of the inverter operation, without affecting the voltage waveforms seen from the electric grid within a wide range of obtainable voltages.

## 3. Proposed control strategy

The proposed control of the three-phase grid-connected TEG system consists of a multi-level hierarchical structure designed in the synchronous-rotating $d$-$q$ reference frame, as depicted in Fig. 6. The control is divided into an external, middle and internal level, each one having its own control objectives [9].

The external level control (left side of Fig. 6) has the goal of rapidly and simultaneously controlling the active and reactive power exchange between the TEG system and the utility grid, through an active power control mode (APCM) and a voltage control mode (VCM), respectively.

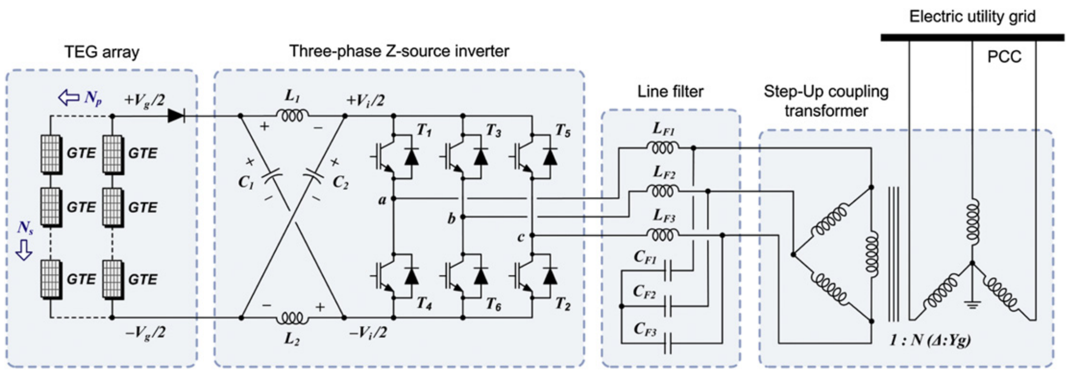


**Fig. 5 – Detailed model of the proposed grid-connected thermoelectric generating system.**

The standard control block of major distributed energy resources is the VCM and consists of a voltage-droop strategy used to modulate the reactive component of the VSI output current, $i_{q1}$ aiming at controlling the voltage at the PCC of the TEG system to the distribution grid. This reactive power control loop employs a standard proportional-integral (PI) controller with droop characteristics for enabling a stable fast-response operation with more devices shunt-connected to the same feeder. In fact, this reactive power is locally generated exclusively by the inverter and can be controlled simultaneously and independently of the active power provided by the TEG.

On the other hand, the main purpose of a grid-tied TEG system is to transfer the maximum available power into the electric system. In this way, the APCM aims at continuously matching the active power to be injected into the electric grid with the maximum instant power capable of being generated by TEG modules, independently of the reactive power generated by the VCM. To this aim, the PCS and its controller must ensure the instantaneous energy balance among all the TEG components. With this objective, a maximum power point tracking (MPPT) is used, whose strategy is based on directly adjusting the shoot-through duty ratio of the Z-source inverter, according to the result of the comparison of successive TEG output power measurements. The control algorithm uses a “Perturbation and Observation” (P&O) iterative method widely used in photovoltaic solar systems with good results and that proves to be more efficient in the case of TEG system applications [4].

The middle level control makes the expected output to dynamically track the reference values ($i_{dr1}$ and $i_{qr1}$) set by the prior external level. This control, which is shown in Fig. 6 (middle side), implements a full decoupled current control strategy of the inverter in the synchronous-rotating *dq* reference frame. To this aim, a linearization of the state-space averaged model of the VSI in *d-q* coordinates (described in-depth in [5]) is employed to design a voltage cross-coupling elimination feed-forward arrangement with

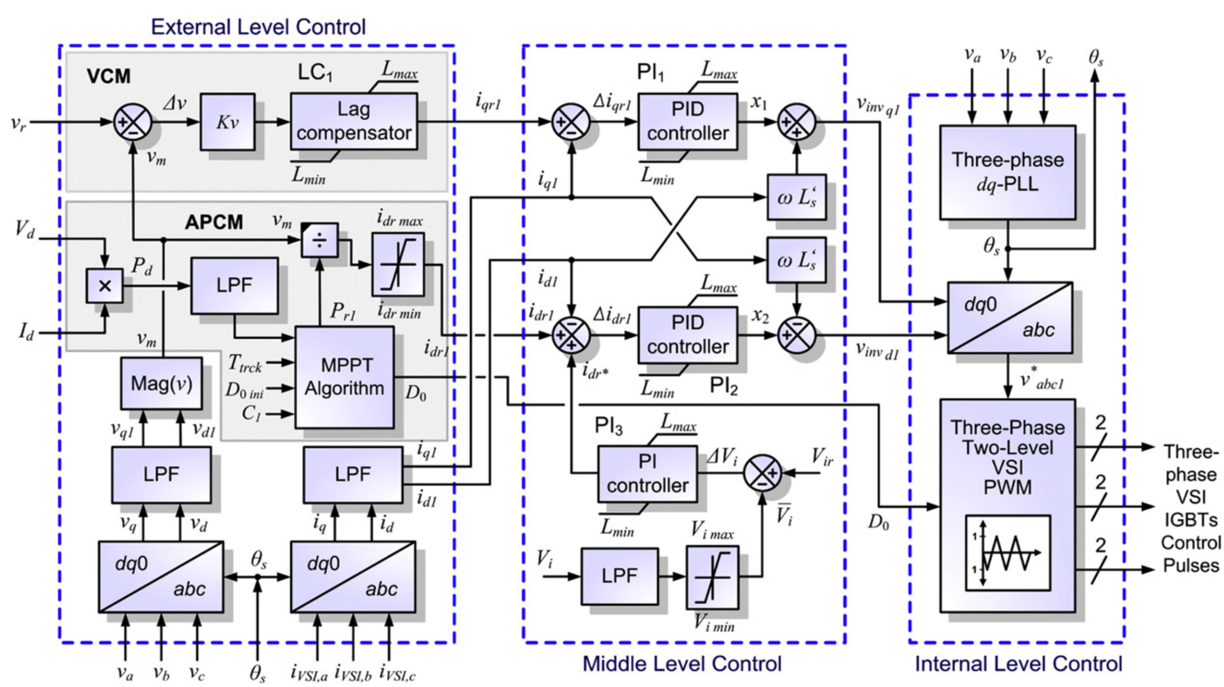


**Fig. 6 – Multi-level control scheme of the three-phase grid-tied thermoelectric generating system.**

two conventional PI controllers ($PI_1$ and $PI_2$). In addition, another PI controller ($PI_3$) is used in order to eliminate the extra coupling resulting from the inverter DC capacitors voltage $V_i$. This is employed in order to eliminate the steady-state voltage variations at the DC bus, by forcing the instantaneous balance of power between the DC and the AC sides of the PCS inverter.

The internal level (right side of Fig. 6) is responsible for generating the switching signals for the six IGBTs of the three-phase two-level Z-source inverter, using a carefully designed carrier-based PWM scheme [9]. This level is also composed of a line synchronization module which consists mainly of a phase locked loop (PLL).

## 4. Digital simulations results

In order to investigate the effectiveness of the proposed developments, dynamic simulations were implemented using SimPowerSystems of MATLAB/Simulink [10]. For full performance studies, independent control of active and reactive power exchanged between the TEG system and the electric grid is carried out. To this aim, two sets of simulations are performed using both control strategies, viz. APCM and VCM.

Simulations depicted in Fig. 7 show the first scenario, which studies only the exchange of active power flow with the utility grid, i.e. only the APCM is activated all the time, for a TEG array composed of a string of 50 TEG modules type HZ-20 (19W at $\Delta T_g = 230-30$ °C) connected to a 380V/50 Hz AC system through the proposed enhanced PCS. The temperature difference between both junctions, $\Delta T_g$ is maintained constant at around 200 °C, but the hot junction temperature, $T_{Hg}$ and consequently the average temperature $T_{Avg}$ is forced to vary quickly in steps every 1s as described in Fig. 7(a). This junction temperature variation produces inversely proportional changes in the maximum power drawn from the TEG array, as described in Fig. 7(b). As can be observed, independently of the internal resistance of the TEG, the P&O algorithm proves to be accurate in following the TEG MPP. The maximum power point for each temperature condition is given by the actual available power, which is rapidly and accurately tracked by the P&O MPPT method. As can be seen from Fig. 7(c), all the active power generated by the TEG system is injected into the grid through the Z-source inverter, except losses, while no reactive power is generated. It is also verified a very low transient coupling between the active and reactive powers exchanged by the grid-connected TEG system due to the proposed full decoupled current control strategy in the synchronous-rotating $d$-$q$ reference frame. Fig. 7(d) depicts the good regulation of the DC bus voltage, $V_d$, which is kept almost constant at about 110 V and independent of the power exchanged with the electric system. Since no reactive power is locally produced by the inverter (VCM deactivated), the voltage at the PCC is maintained almost invariant at 0.99 p.u. (base voltage of 380 V), as shown in Fig. 7(e).

Simulations of Fig. 8 show the second scenario, which study the simultaneous and independent exchange of both, active and reactive power flow with the distribution grid, i.e. the APCM is activated all the time as in the prior case study while the VCM is activated at $t = 0.6$ s. The TEG array is now

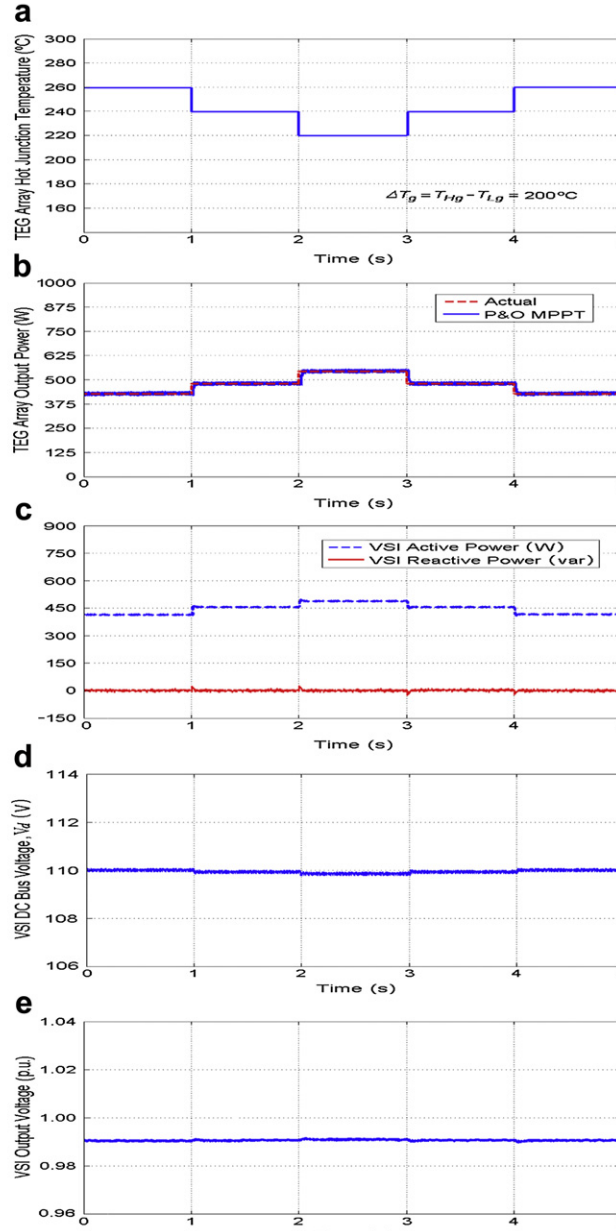


**Fig. 7 – Simulation results for active power exchange with the utility grid (APCM): (a) TEG array hot junction temperature. (b) TEG array output power. (c) Inverter active and reactive power. (d) Inverter DC bus voltage. (e) PCC terminal voltage.**

subjected to the same previous profile of junction temperature variations, as described in Fig. 8(a). As can be observed from Fig. 8(b), the maximum power for each temperature condition is rapidly and accurately drawn by the P&O MPPT method in the same way as in the preceding case study. As can be observed from Fig. 8(c), this power is injected into the electric grid through the Z-source inverter, except losses, which are increased when reactive capacitive power is also generated by the VCM, causing a slightly lower exchange of active power than the previous case studied. As can be observed from comparison with the preceding case results, all DC

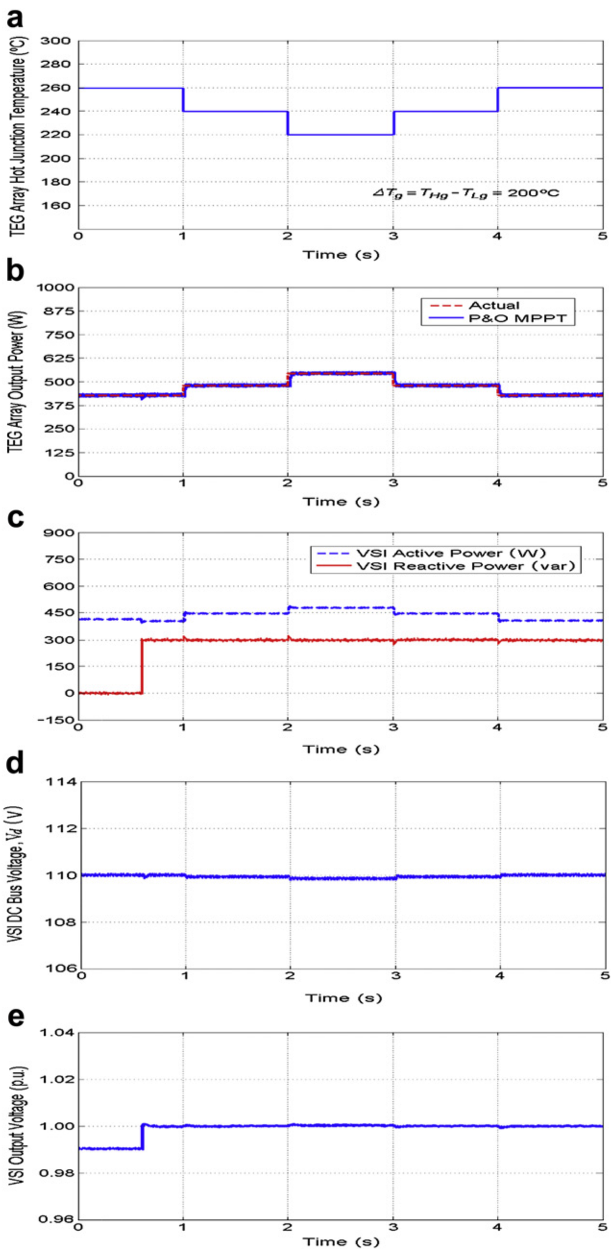


**Fig. 8 – Simulation results for active and reactive power exchange with the utility grid (APCM and VCM): (a) TEG array hot junction temperature. (b) TEG array output power. (c) Inverter active and reactive power. (d) Inverter DC bus voltage. (e) PCC terminal voltage.**

simulations do not change, because the DC bus voltage is kept almost invariable at about 110 V and independent of the power exchanged with the electric system, as shows Fig. 8(d). This is a consequence of the proposed controller, which isolates the DC part from the AC part of the Z-source inverter. Thus, a full decoupled current control of the Z-source inverter in the synchronous-rotating *d-q* reference frame is achieved and consequently of the active and reactive power injected into the AC grid. The good performance of the voltage regulator of the TEG device is evidently depicted Fig. 8(e) through the rapid compensation of 300 var of reactive power, which permits to quickly regulate the instantaneous voltage at the PCC from 0.99 p.u. up to 1 p.u. (base voltage of 380 V).

## 5. Conclusion

A novel power conditioning system of a grid-connected TEG system to simultaneously and independently control the active and reactive power flow in the distribution grid has been studied and implemented. A real detailed model and a novel multi-level control scheme based on a full decoupled current control of the inverter in *d-q* coordinates with an MPPT control of the TEG array were proposed. Dynamic system simulation studies demonstrate the effectiveness of the proposed models and control algorithms. The fast response of the PCS and the enhanced performance of the described control techniques allow taking full advantage of the TEG system as a distributed generator. The presented single-stage PCS topology with self-boost capabilities offers a simple and effective alternative over the conventional two-stage one for interfacing the TEG devices with the AC utility grid. The advantages of this topology include a better power conversion efficiency, higher reliability, inherent short circuit protection and a reduction of the volume and weight of the entire system.

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